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11. SUPPLEMENTARY NOTES
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12 a. DISTRIBUTION / AVAILABILITY STATEMENT

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13. ABSTRACT (Maximum 200 words)

To develop a fundamental understanding and quantitative assessment of the dynamic response and failure modes of highly heterogeneous and anisotropic composites of ceramics, cermets, metals, and fiber-reinforced polymeric composites, various specific complementary scientific tasks have been initiated by the participating team members, based on their strengths and expertise. These tasks include development of novel experimental techniques, preliminary experiments, development of micromechanically-based models, and computational tools. As research progresses, these efforts will be continued and will be integrated, in order to effectively achieve the basic goals of this MURI. While the team members have collaborated with each other in various relevant research areas, each one has emphasized one or two necessary research areas, as follows:
Sia Nemat-Nasser: Dynamic experiments (Hopkinson/gas gun); dynamic failure of fiber-reinforced polymer composites; micromechanical modeling of compression-induced failure modes of anisotropic heterogeneous ceramics; and modeling of anisotropic effects in pulverized, initially heterogeneous, ceramic layers; *Marc Meyers:* Synthesis and processing of TiC-NiTi and TiB_2-NiTi composites; constitutive description of porous ceramics; and quasi-static and dynamic testing of composites; *Vitali Nesterenko*: Thick-walled cylinder experiments on various grades of SiC; experimental investigation on nonexplosive, shear-induced chemical reactions in various relevant compounds; and micromechanical modeling of hot isostatic pressing of metallic alloys; *Ken Vecchio:* Fabrication of titanium-aluminide composites; microstructural characterization; and preliminary modeling; *Dave Benson:* Computational techniques to efficiently integrate various coupling physics into computational codes, including reactive flow models, statistical crack mechanics, and improved integration of finite deformations.

14. SUBJECT TERMS
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I. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES.

The following manuscripts, submitted for publication, in press, and published, were prepared wholly or partially under the sponsorship of the Army Research Office for the research period of 1996-2002.

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- Meyers, M.A., D.J. Benson, O. Vöhringer, B.K. Kad, Q. Xue, H.H. Fu, and Y.J. Chen, "Constitutive Description of Dynamic Deformation: Physically-Based Mechanisms," *Matls. Sci. and Eng.* (2002).
- Benson, D.J., H.H. Fu, and M.A. Meyers, "On the Effect of Grain Size on Yield Stress: Extension into Nanocrystalline Domain," *Matls. Sci. and Eng.* (2002).
- Xue, Q., M.A. Meyers, and V.F. Nesterenko, "Self-Organization of Shear Bands in Titanium and Ti-6% Al-4% V Alloy," *Acta mater*, 2002.
- Nemat-Nasser, S., "Dislocation-Based Rate- and Temperature-Dependent Deformation of fcc, bcc and hcp Metals," *Proceedings of the ICES2K*, Los Angeles, Ca. August 2000.

C. Submitted

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(Note: Many of the above referenced papers also acknowledge other contract and grants. If this information was known, at the time of that this list was compiled, then these other contracts/grants have been noted**).**

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II. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD

Post-doc's and Visiting Research Scholars:
- Jingyi Cheng, Visiting Researcher (Nemat-Nasser) 1999 - 2000
- Weiguo Guo, Visiting Researcher (Nemat-Nasser) 1996 - 1999
- Sastry Indrakanti, Post-Doc (Nesterenko) 1997 - present
- Rajeev Kapoor, Post-Doc (Nemat-Nasser) 1998 - 1999
- Yulong Li , Visiting Researcher (Nemat-Nasser) 1996
- Mingqui Liu, Post-Doc (Nemat-Nasser) 1996-1997
- Qingchi Liu, Post-Doc (Meyers) 1999 - 2000
- Aashish Rohatgi, Post-Doc (Vecchio) 9/99 - present)
- Andrew Strutt, Asst. Proj Scientist (Vecchio)
- Juhua Zhang, Post-Doc (not supported) (Nemat-Nasser) 1999 - 2001

MURI Consultant:
Prof. Werner Goldsmith, UC Berkeley 1996 - 2001

Graduate Students:
Dave Benson (Advisor)
- Ian Hoang-Phuc Do 1997 - 1999
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Marc A. Meyers (Advisor)
- Rainer Menig (U. of Karlsruhe, Germany)
- Marc H. Meyers (UCSD Biology Dept)
- James Shih (IMM Pre-Doctoral Researcher) 1996 - 1998
- Elizabeth (Kristofetz) Strutt (MURI Fellowship)1996 - present
- Qing Xue 2000 - 2001

Sia Nemat-Nasser (Advisor)
- Jeff McGee 1998 - 2001
- Jacob Rome 2000 (UCSD Fellowship)
- Sai Sarva 1996 to present

Vitali Nesterenko (Advisor)
- Yong Liu 1996 - 1998
- Gu Yabei 10/98 - present

Ken Vecchio (Advisor)
- David Harach 1998 to 2001 (MURI Fellowship)
- Aashish Rohatgi 1996 - 1999

Degrees Received During This Reporting Period:

- Yong Liu 1998 MS via examination
- James Shih 1998
- Ian Do Spring 1999 Ph.D. Thesis - Shock Induced Chemical Reactions of Multi-Material Powder Mixtures: An Eulerian Finite Element Computational Analysis"
- Aashish Rohatgi Fall 1999 Ph.D. Thesis

- David Harach Fall 2000 Ph.D. Thesis - Processing, Properties and Ballistic Performance of Ti-Al3 Ti Metal Intermetallic Laminate (MIL) Composites"
- Qing Xue, Fall 2001: Ph.D. Thesis - Spatial Evolution of Adiabatic Shear Localization in Stainless Steel, Titanium and Ti-6AI-4V Alloy"
- Jeff McGee, Summer 2002 Ph.D. Thesis - Mechano-electromechanical response of Ionic Polymer Metal Composites"

III. REPORT OF INVENTIONS (BY TITLE ONLY):

- Vecchio, K.S., U.S. Patent Application: "Process for Making Metallic/Intermetallic Composite Laminate Materials, and Materials so Produced Especially for Use in Lightweight Armor" Application filed Aug. 6, 1998, expected to issue early 2002.

IV. BRIEF OUTLINE OF RESEARCH FINDINGS FOR THIS REPORTING PERIOD

Introduction

The work at UCSD involved a collaborative research effort addressed the following interconnected aspects:

1) Synthesis and processing of armor materials and composites; 2) Experimental characterization; 3) Development of new experimental techniques; 4) Analytical and computational modeling of the basic failure mechanisms; 5) Computational simulation of experiments; and 6) Tests of composite models

SCIENTIFIC ACCOMPLISHMENTS UNDER CEAM (Sia Nemat-Nasser, PI)

Research directed by Prof. Sia Nemat-Nasser
Supporting graduate students: Sai Sarva and Jeff McGee, Research Engineers Jon Isaacs and David Lischer, and Postdoctoral Researcher Juhua Zhang.
Collaborators: Vitali Nesterenko, Marc Meyers, and David Benson

Four Major areas, under Sia Nemat-Nasser's supervision, are as follows:

- Novel Instrumentation and Measurement Techniques for High Deformation Rate Phenomena
- Understanding and Experimental Quantification of the Effect of Front-Face Constraint by Thin-Membrane (E-glass/Epoxy, Ti-3/2.5 and Carbon-fiber/Epoxy) on the Ballistic Performance of Armor Ceramic Tiles
- Dislocation-Based Micromechanical Modeling of Titanium Alloys with Extensive Experimental Verification
- Micromechanics of High Strain-Rate Compression Failure of Ceramics

1.0 Novel Instrumentation and Measurement Techniques for High Deformation Rate Phenomena

1.1. Development of dynamic tri-axial Hopkinson bar

A technique has been developed for dynamic testing under tri-axial compression[1]. A Hopkinson bar has been modified to simultaneously load the sample in radial and axial directions. It consists of larger (27.1 mm) and smaller (19.1 mm) incident bars and transmission bars as seen in Fig. 1. Incident and transmission tubes which encompass the smaller incident and transmission bars, but move independently of them, help load a Teflon sleeve. The Teflon sleeve surrounds the sample and is restricted by an aluminum sleeve on the outside. The sample is machined to be the same diameter as the smaller incident and transmission bars. During the test, a large hydrostatic stress is induced in the Teflon sleeve, which in turn exerts a large radial stress on the sample. The radial stress increases during the test, as the incident and transmission bars axially load the sample and the Teflon sleeve. Due to the radial expansion of the sample during deformation, the Teflon sleeve is pre-slit to help recover the sample without any damage. The radial stress is estimated by measuring the hoop strain in the aluminum sleeve. Appropriate solutions are used to calculate the radial stress,

depending on if the hoop strain falls in to the elastic, elastic-plastic or plastic regime. A strain rate of 600 s^{-1} and radial stress of 100 MPa have been attained, while studying samples such as mortar.

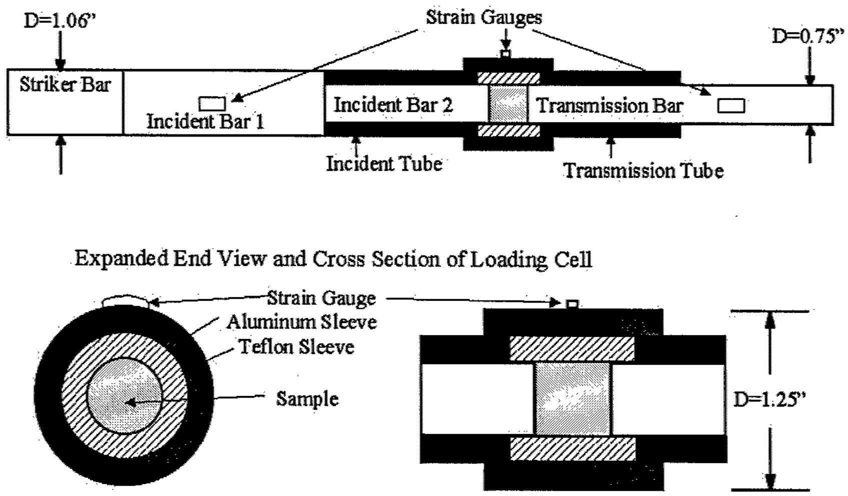


Figure 1. Tri-axial test configuration

1.2. Dynamic Characterization of High Velocity Impact and Penetration Phenomena
1.2.1 Development of a gas-gun with the capabilities of measuring initial and residual projectile velocities

A single stage gas-gun has been developed at the CEAM underground impact laboratory. The barrel diameter is 2.54 cm and the length is 5 m. The driving gas is Helium. It is capable of launching a projectile at velocities of more that 1000 ms^{-1}. Two velocity sensors at the muzzle end of the barrel, help measure the initial velocity of the projectile. They also help trigger the high-speed digital camera and X-ray head circuitry. After penetration of the target, the eroded projectiles exit from the rear surface. Two magnetic coil velocity sensors help measure the residual velocity of the projectile. The eroded projectiles are recovered using paper stacks as momentum dump. Two configurations of target assembly have been developed:

i) The stripped-sabot configuration – Aluminum sabot carries the projectile through the barrel. Prior to impact, the sabot is stripped by means of a maraging steel stripper. This configuration helps evaluate the ballistic performance of the target. See Fig. 2.
ii) The unstripped-sabot configuration – The sabot is left unstripped. This reduces the sabot debris and results in immaculate imagery of the initial stages of penetration, thus helping understand the failure phenomenon.

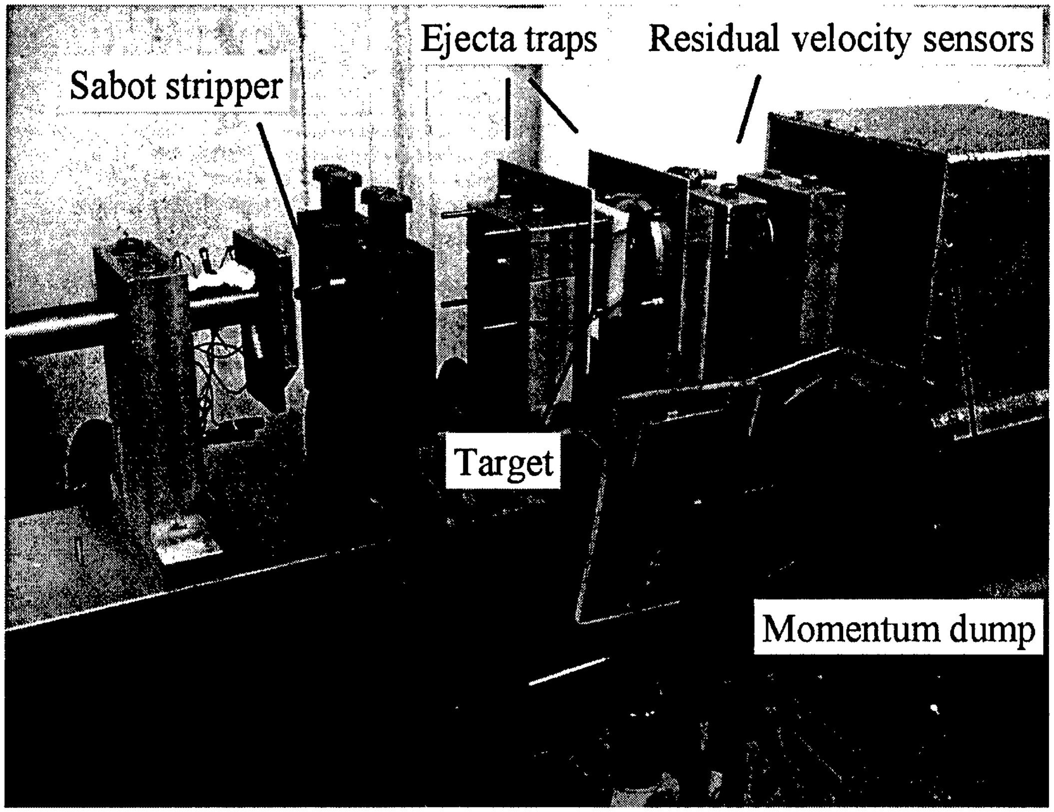


Figure 2. Stripped-sabot configuration for ballistic tests

1.2.2 Integration of impact phenomena with high-speed photography of the front and back face temporal response of the target

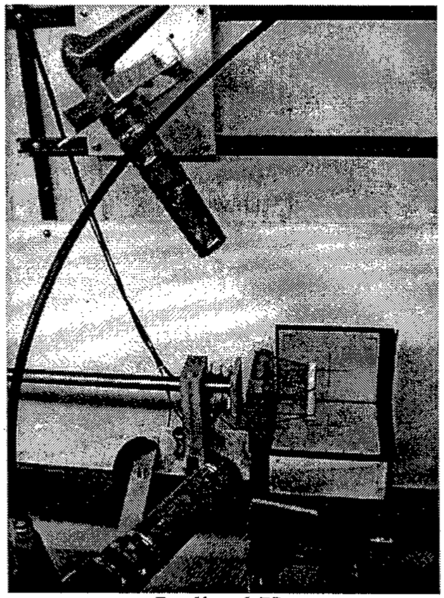
The Hadland Imacon 200 high-speed digital camera has been used to study the ultra-high speed phenomenon of ballistic failure. The camera can be programmed to record a sequence of separate images at prescribed time intervals. A sixteen-channel camera was used. The camera is triggered indirectly by the velocity sensors on the barrel, thus capturing images of the penetration event with precision timing. Images acquired from a point of view normal to the path of projectile, help study the front and rear surface characteristics of the ejecta flow, which occurs during penetration of ceramic targets. Accompanying software helps image analysis through displacement and velocity measurement tools.

1.2.3 Flash radiography of penetrator-target interaction

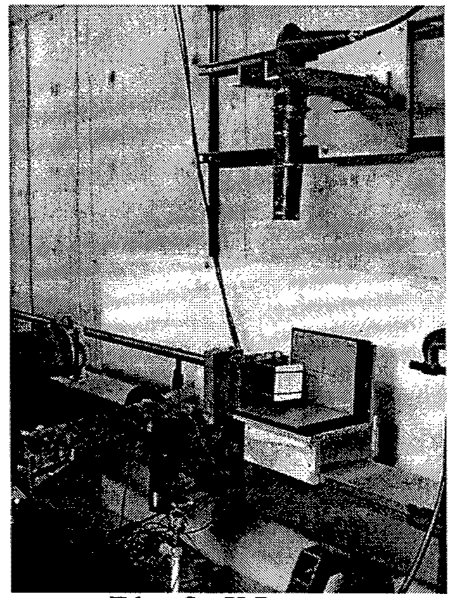
Flash radiography procedures have been developed to study the projectile-target interaction during penetration. The X-ray heads (100kV and 450 kV) are also triggered by the velocity sensors on the barrel, thus providing dynamic real time images of the projectile penetrating the target. Two configurations have been used:

i) Inclined X-ray – The X-ray heads are placed inclined to the path of the projectile. This reduces the ceramic cross-section that is pierced by the X-rays and helps study the interior of the target during penetration. See Fig. 3.

ii) Edge-on X-Ray – The X-ray heads are placed orthogonal to the path of the projectile. Since the target thickness is large, the interior is not revealed but it helps study the flow of rod erosion products emerging from the front surface.



Inclined X-ray



Edge-On X-Ray

Figure 3. Flash radiography configurations

2.0 Understanding and Experimental Quantification of the Effect of Front-Face Constraint by Thin-Membrane (E-glass/Epoxy, Ti-3/2.5 and Carbon-fiber/Epoxy) on the Ballistic Performance of Armor Ceramic Tiles

Experiments[2] were performed to study the effect of thin membrane constraint on the ballistic efficiency of armor grade 12.7 mm thick Al_2O_3 tiles. WHA was used as the projectile material. Impact velocity was maintained at approximately 900 ms^{-1} for all the tests. Various materials were used as the front-face constraining membrane. The thickness of the constraining membrane was varied too. Stripped-sabot tests were performed to evaluate the ballistic efficiency. The kinetic energy fraction (fKE, f_{KE} = residual K.E/ initial K.E) was calculated. Fig. 4. shows the experimental results. As can be seen, the front-face restraint improves the ballistic efficiency dramatically. The ballistic efficiency also improves with increasing thickness of the membrane layer. As can be seen, the f_{KE} for the bare tiles is 0.35. The f_{KE} for a three layer E-glass/Epoxy pre-preg fabric constrained sample is 0.12. This is a nearly 23% improvement in the ballistic efficiency for a mere 2.5% increase in areal density.

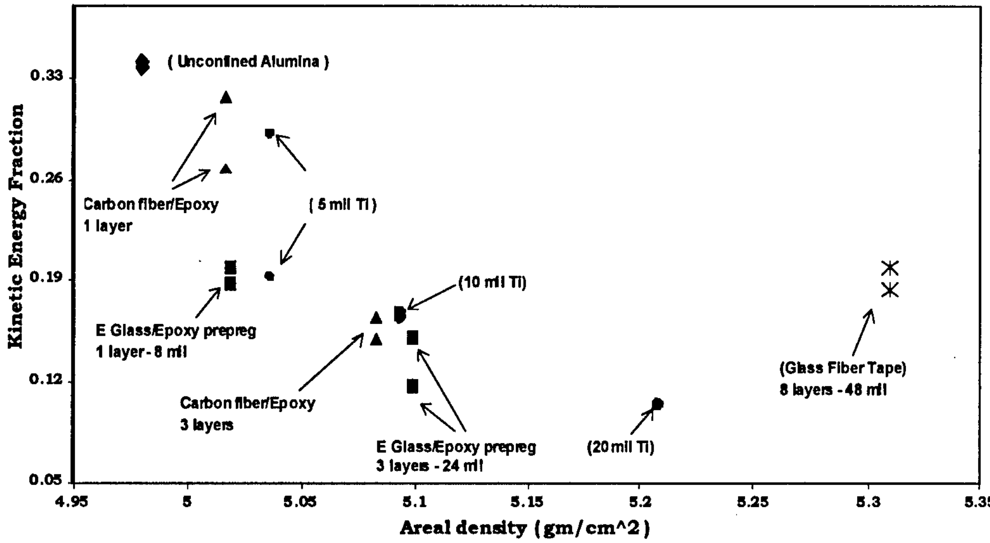


Figure 4. The effect of front-face constraint on the ballistic performance of allumina tiles

High-speed photography indicates that the front-face ejecta flow is vastly altered by membrane constraint. The ejecta flow for a bare tile is radially disperse, and conical in shape. Constraining the tile results in a much more restricted movement of the ejecta, further resulting in a flow that is acute and cylindrical in shape. The ejecta velocity for the constrained sample is nearly 40% higher during the intial stages of penetration. Flash radiography indicates that the projectiles undergo much greater mushrooming and erosion for a constrained sample, indicating increased penetration resistance.

3.0 Micromechanics of High Strain-Rate Compression Failure of Ceramics

The dynamic compressive strength and failure mechanisms in ceramics have been studied.[3, 4] Experiments have been conducted on SiC under uni-axial compression from strain-rates ranging from 10^{-4} to 9000 s^{-1}. Quasi-static tests were performed on an Instron test machine. Strain-rates of up to 1200 s^{-1} were reached on a 12.7 mm Hopkinson bar. Ultra high strain-rate experiments were conducted on a mini Hopkinson bar (4.76 mm in diameter) to study SiC under uni-axial loading at a strain-rate of nearly 9000 s^{-1}. The compressive strength was observed to improve from 4.2 GPa under static loading conditions to 8.5 GPa at a strain rate of 9000 s^{-1}. The samples failed by axial splitting. Nucleation of micro-cracks from pre-existing flaws such as inclusions, pores and grain boundaries, and their subsequent coalescence results in fragmentation. The fragment size was found to be sensitive to strain rate. It decreased with increasing strain rate, indicating that a many more micro-cracks are nucleated during a dynamic test.

Also, the compressive strength of SiC was studied under multi-axial loading. A confining pressure of 300 MPa was attained by a double-sleeve confinement method. The confinement resulted in an improvement of nearly 2 GPa in the compressive strength. The strain-rate sensitivity of the compressive strength is maintained. Unlike the unconfined samples, the confined samples failed by fault formation, due to a preferential crack growth. The experimental results have been analyzed using a micro-mechanical model, previously developed by Nemat-Nasser and Deng.[5] They consider an array of interacting wing-cracks, which describes the influence of micro-structure on the dynamic behavior of ceramics. The microstructure is described in terms of average flaw-size and flaw spacing. The experimental results have been compared to the model and it has been observed that the model provides a quantitative description of the results. Fig. 5. shows the experimental results and the comparison to the model. The model has been plotted for a flaw size of 90 μm and a flaw spacing of 950 μm.

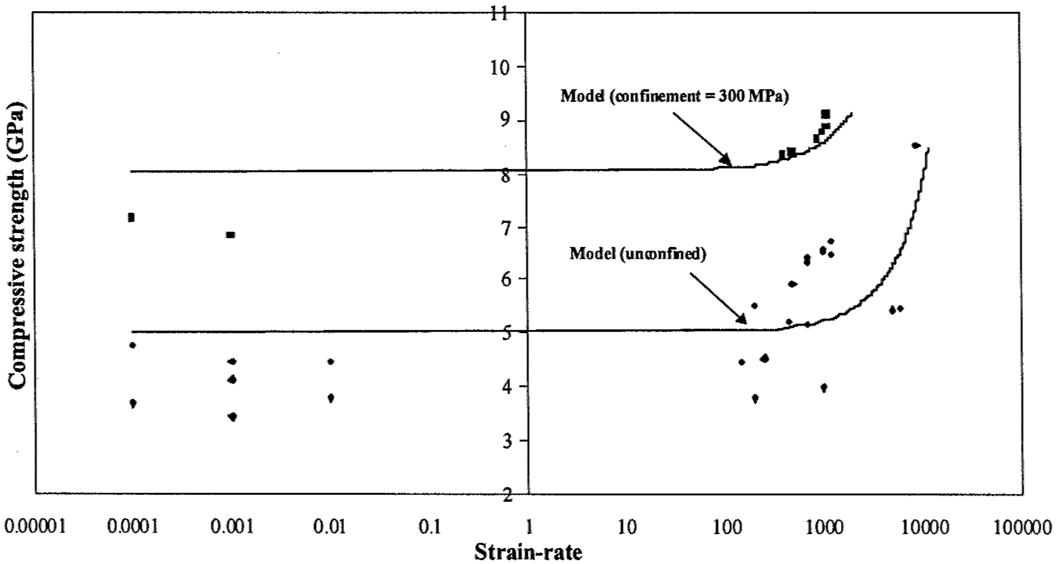


Figure 5. Experimental results and comparison to wing-crack array model

4.0 Dislocation-Based Micromechanical Modeling of Titanium Alloys with Extensive Experimental Verification.

Extensive research has been conducted to study the dynamic response of conventional and iso-statically hot-pressed Ti-6Al-4V (Ti-6/4) alloys.[6] The thermo-mechanical response of Ti-6/4 alloys with three different microstructures was studied. Experiments were performed from a strain-rate of 10^{-3} to 7000 s^{-1}. The Instron test machine was used for the quasi-static tests and the modified split-Hopkinson bar was used for the dynamic tests. The temperature was varied from 77 K to 1000 K. The microstructure of the failed and unfailed samples was examined by optical microscopy. It was observed that depending on the temperature, shear bands are formed when the sample is deformed to large strains. The flow stress was observed to be more sensitive to temperature than to strain-rate. A physically based model proposed by Nemat-Nasser and Li[7] for OFHC copper was suitably modified and applied to Ti-6/4. It was concluded that the initial microstructure affects only the magnitude of the threshold stress and the athermal part of the flow stress but not the dependence of thermally activated part of flow stress on the strain-rate and temperature.

Similar experiments have also been performed on commercially pure Titanium (CP-Ti). [8] It was observed that the flow stress of CP-Ti is strongly dependent on strain-rate and temperature. A two-stage deformation pattern was seen at temperatures below 296 K. A complex three-stage deformation was observed at temperatures within the range 296-800K and a single stage deformation was seen at temperatures above 800K. Interrupted tests involving temperature jumps were performed to understand the underlying mechanisms and it was concluded that the three-stage deformation pattern was a result of dynamic strain-aging, caused due to the interaction between moving dislocations and mobile point defects in the dislocation core area. Also substantial deformation twinning was observed. A model was developed to describe the experimental results both qualitatively and quantitatively.[9] The model combined the concepts of athermal long-range and thermally activated short-range barrier with the model of a 'trough' for the thermally activated breakaway of dislocations from the core atmosphere. This unified model accurately predicts the response of CP-Ti over a range of temperatures and strain-rates. See Fig. 6.

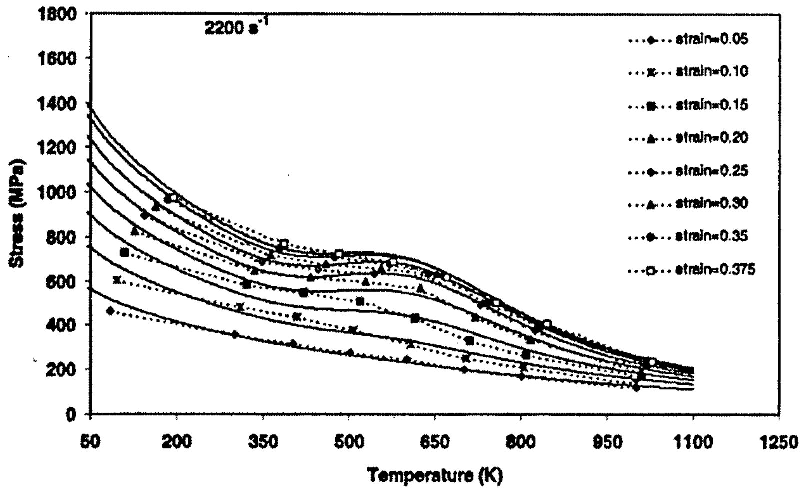


Figure 6. Flow stress vs temperature curves for CP-Ti
(dotted line: experimental, solid lines: theoretical)

Remarkably, similar but more complex response has been observed in commercially pure molybdenum, involving several ranges of temperatures within which dynamic strain-aging has been observed[10].

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REPORT DOCUMENTATION PAGE (SF298)
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SCIENTIFIC ACCOMPLISHMENTS UNDER DIRECTION OF PROFESSOR DAVID BENSON

Computational Simulation of Experiments

Research directed by Prof. David Benson
Supporting graduate student Hsueh-Hung (Edward) Fu
Collaborators: Vitali Nesterenko and Marc Meyers

The two-dimensional Eulerian finite element program is being re-written to handle three-dimensional problems. Based on the current rate of progress, the first calculations will probably be June 2000. This project is motivated by the three-dimensional nature of the materials being investigated in the MURI project, e.g., K. Vecchio's corrugated MIL composite and V. Nesterenko's titanium reinforced with ceramic cylinders.

1.0 Analytical and Computational Modeling

Research involved simulating the effect of the cell size on the shock wave attenuation in laminated composites. The composites are composed of Cu+Al and Al+Ti. It was found that under similar impact conditions, there is a strongly nonlinear effect, namely the amplitude of the leading wave increases as the cell size decreases. This behavior is in a drastic contrast with the expected response based on a linear acoustic analysis or on an analysis based only on the leading shock interaction with interfaces. This effect is typical for any laminated composite under strong shock loading, and was earlier experimentally observed for the Cu+Al system. The calculations for this material qualitatively agree with the experiments.

A comparison of bonded and unbonded laminated composites demonstrated that short waves (their duration is comparable to the propagation time through one cell) attenuates faster in a bonded composite than in an otherwise identical, but unbonded system. Shock waves of a much longer duration attenuate in a similar manner in bonded and unbonded systems.

Vitali Nesterenko and Dave Benson are continuing their investigation of the cold densification of powders. P. Haussmann has graduated from UCSD with his MS degree in mechanical engineering and returned to Switzerland. Alma Martinez King, an undergraduate student funded by the Mc Nair Program, is continuing his work on this project.

Marc Meyers, Dave Benson, and Hsueh-Hung Fu are modeling the effect of grain size on the flow stress in metals. Individual grains are modeled discretely, with the grain boundary having different material properties than the interior of the grain. The grains are generated using a Vornoi construct, and then subjected to compressive loading. Initial calculations were performed explicitly at a moderate strain rate, and we are currently comparing the results to quasi-static calculations performed with the recently added implicit Eulerian formulation.

SCIENTIFIC ACCOMPLISHMENTS UNDER DIRECTION OF PROFESSOR KENNETH VECCHIO

1.0 Development of a New Materials System termed '*Metallic-Intermetallic Laminate (MIL) Composites*'.

The most significant contribution from Professor Vecchio's group was the development of an entirely new materials system that was bio-mimetically inspired based on the structure of seashells, notably the abalone and conch shell structures. These shell structures consist of hard, brick-like calcium carbonate regions called 'nacre', interlaced in a layered morphology with a viscoelastic protein glue. The individual components of the shells, the nacre and protein, have rather poor mechanical properties, however the unique

architecture of the layered and 3-D morphology of the structure imparts significant strength, hardness, and fracture toughness to these shells. Figure 1 shows a micrograph of the structure of an abalone shell.

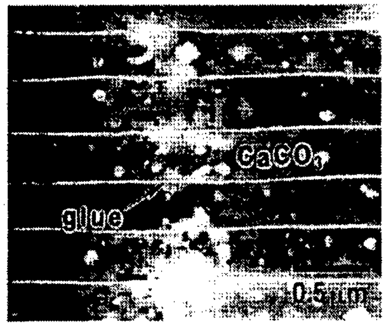


Figure 1. TEM micrograph of the structure of an abalone shell.

Recognition of the role of the architecture in enhancing the properties of the shells inspired us to create a materials system that 'mimicked' the structure of the shells, but composed of materials with significantly better mechanical properties for their individual components. Based on some earlier work by U. Anselmi-Tamburini and Z.A. Munir attempting to create monolithic intermetallic materials from co-rolled metal foils, a concept was developed for creating layered metal and intermetallic structures from a foil metallurgy approach. The unique properties of MIL composites arise from the combination of the high hardness and stiffness of the intermetallic-aluminide phase alternatively layered with the good strength, toughness, and ductility of metal alloys. Figure 2 shows examples of the wide range of layer thickness and phase volume fraction the can be achieve routinely in these metallic-intermetallic laminate composites based on the Ti-Al system.

In the case of Ti-Al MIL composites, the specific stiffness (modulus/density) is nearly twice that of steel, the specific toughness and specific strength are similar or better than nearly all metallic alloys, and specific hardness is on par with many ceramic materials. An interesting comparison of material properties for the MIL Composites can be obtained using an Ashby-type plot of compound material properties. Figure 3 shows a plot having the x-axis a compound function of specific material properties related to structural behavior (tensile strength, modulus, fracture toughness, all divided by density) and the y-axis a compound function of specific material properties related to blast and/or protection (compressive strength and hardness divided by density). In this plot numerous material locations are shown, and in terms of optimizing both the structural properties and protection properties, the upper right-hand corner represents the goal.

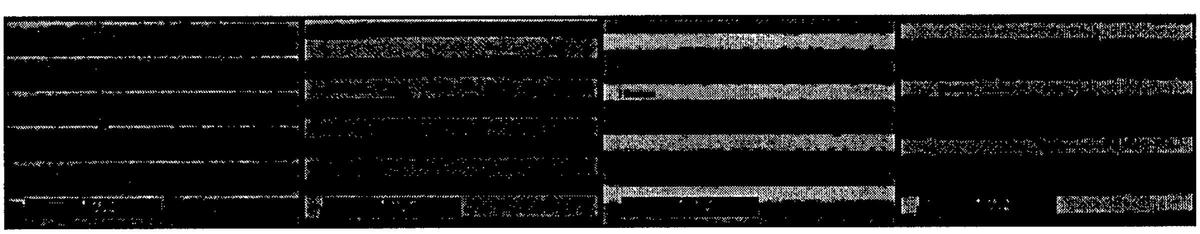


Fig. 2. Representative backscattered electron micrographs of Al-Ti composites showing the variation in layer thickness and phase volume fraction that can be achieved simply by the selection of initial foil thickness.

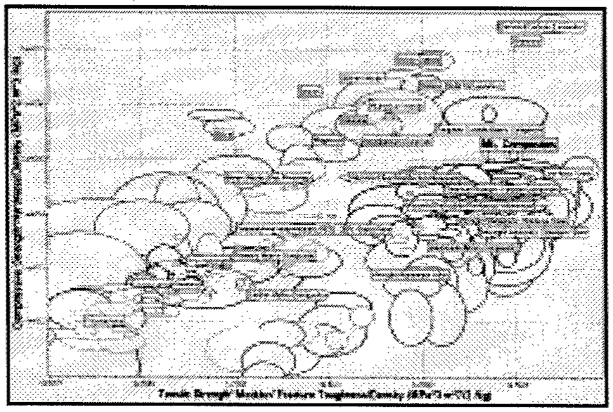


Fig. 3. Materials property map comparing structural versus blast/ballistic property indexes.

The location of the MIL composites is shown close to the optimized corner of the plot, and clearly demonstrates the tremendous potential of the MIL composites for structural/blast applications. MIL composites are fabricated by a reactive foil sintering technique, in open air, using commercially available metallic foil and sheet materials, which makes the processing and resulting materials low cost. The selection of the foil materials is based on metallic systems that form aluminides, and to date large-scale MIL composites have been fabricated from Ti-Al, Ni-Al, Fe-Al, Cu-Al and shape memory NiTi-Al systems, although it appears it will work for any metal-aluminide system. The composition, physical, and mechanical properties of the MIL composites can be varied and tailored within the thickness of the composite by simply varying the individual foil compositions, thickness, and layering sequence. The fabrication of metallic-intermetallic laminate (MIL) composites using this approach has several key advantages that make it ideally suited for the production of commercially scalable structural materials.

First, since the initial materials utilized are in the form of commercially available metallic foils, the initial material cost is reasonably low, compared to many of the exotic material processing routes that are commonly pursued in small-scale research environments.

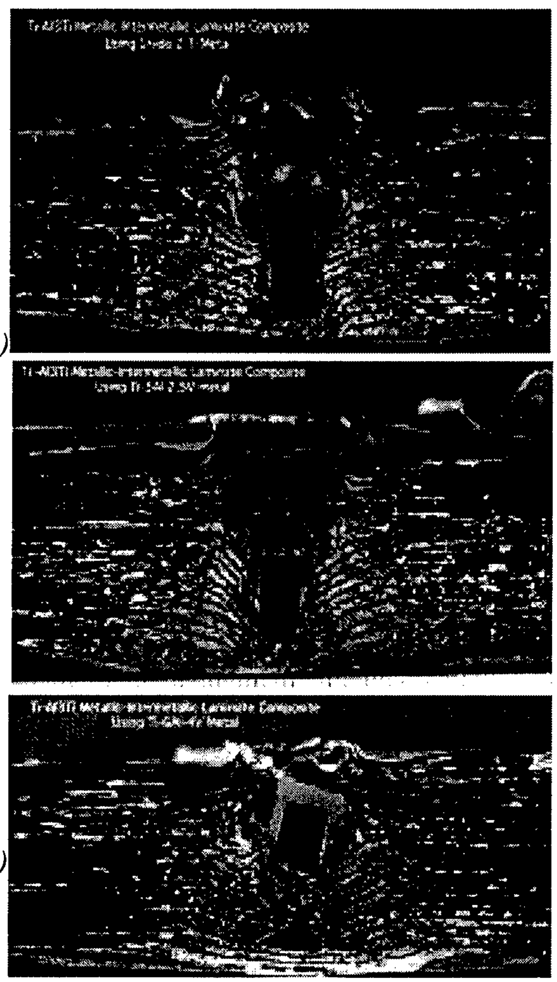
Second, the use of initially ductile metallic foils enables the layers to be formed into complex shapes. This opens the door for non-planar (corrugated layered) structures, simple machining of individual foils for complex, 3-dimensional structures, and near-net shape forming of parts.

Third, the processing conditions, in terms of temperature, pressure and atmosphere are very modest. Processing temperatures, in the case of Al foils containing samples is below 700°C, and the processing pressures are below 4 MPa. Perhaps the most remarkable feature of the processing of these metallic-intermetallic laminate composites is that the processing is carried out in open air, no special inert gas or vacuum chamber facilities are necessary. The combination of these various processing features makes the processing method itself very low cost, and easily amenable to computer control.

Fourth, the microstructure of the metallic-intermetallic laminate composites is determined by the foil thickness and composition and the processing condition. Since the material make-up is based on the selection of the metal foils, it is possible to completely tailor the microstructure from one surface to the other. In addition, since the MIL composites are made using metallic foil starting materials, complex and near-net shape formed parts can be fabricated readily by forming the individual metal foils prior to the reactive sintering process.

2.0 Structural Armor Material

For armor applications, these metallic-intermetallic laminate composites offer several key features that are essential for improved ballistic performance. Although the initial components are metal foils, the reaction produced a hard, lightweight intermetallic (e.g. aluminide) phase. The volume fraction and layer thickness of this intermetallic phase is controlled by the foil thickness. Since the intermetallic phase is formed from the metallic foils, its morphology takes on whatever morphology the initial foils possessed (i.e., corrugated foils produce corrugated intermetallic layers). The intermetallic phase, although hard and brittle by nature, is contained and constrained by the remnant, unreacted metal (e.g. Ti) layers. As such, during ballistic impact the microcracking of the intermetallic layers ahead of the penetrator does not result in catastrophic fracture of the material (as happens with monolithic ceramic or intermetallic plates). So although the intermetallic layers fragment within the material, they continue to interact with the penetrator, slowing, eroding, and deflecting the penetrator. Finally, the remnant metal layers significantly increase the inherent fracture toughness of the composite, thereby increasing the energy absorption capacity of the material. Figure 4 shows a series of three photographs of cross-sections through MIL composite samples impacted by 10-gram WHA penetrators at a velocity of 900 meters/second. The sequence shows samples fabricated from Grade 2 Ti foils, (~50ksi. yield strength), Ti-3Al-2.5V foils (~90 ksi. yield strength) and Ti-6Al-4V foils (~145 ksi. yield strength), all initially 0.020" thick reacted with 1100 series Al foils of initial thickness 0.024", yielding composites containing approximately 20 vol.% Ti and 80 vol.% intermetallic (Al_3Ti).



(a)

(b)

(c)

Fig. 4. Three photographs of cross-sections through MIL composite samples impacted by 10-gram WHA penetrators at a velocity of 900 meters/second. (a) Sample fabricated from Grade 2 Ti foils, (b) Ti-3Al-2.5V foils and (c)Ti-6Al-4V foils.

The samples have initial areal densities of approx. 7 grams per cm^2. The samples were tested in a Depth-of-Penetration (DOP) configuration with a steel backing plate at 0.10" standoff. In each case the penetrator was stopped within the target, with the depth of penetration decreasing with increasing Ti metal layer strength. In the case of the Ti-6-4 MIL composite, the penetration depth is less than 1 cm., suggesting that the penetrator would have been stopped with a plate somewhat less than the initial 2 cm. thickness, and perhaps as low as 1 to 1.5 cm. thickness. Since the density of these MIL composites is 3.5 gm/cm^3, a one-centimeter thick plate has an areal density of *3.5 $gm./cm^2$*.

3.0 Corrugated MIL Composites for Enhanced Penetrator Deflection

A novel and important ballistic feature of these MIL composites is the ability to form materials in which the layered structure is inherently oblique to any incoming projectile. Corrugated materials have the added advantage of being structurally stiffer, than the corresponding material in flat plate form. The individual foils can be initially formed into any complex shape, such as corrugated sheets, stacked together and reacted. Fig. 5 shows an example of a corrugated MIL composite, along with a cross-section through a projectile impact location. The influence of the oblique corrugated layers is evident by the significant tilting and deflection of the penetrator. The penetrator used in this ballistic test was a NATO 308 AP round fired at 700m/s. The lateral deflection is approximately 2.5 cm, in a plate that was only 2.5 cm thick.

4.0 Through-thickness Strengthening of MIL Composites

Concepts for direct control of through-thickness strength includes metallic wire stitching. Prior to processing, the entire metal foil stack can be places in a CNC end-mill and have a pre-designed array of small holes drilled through the entire foil stack.

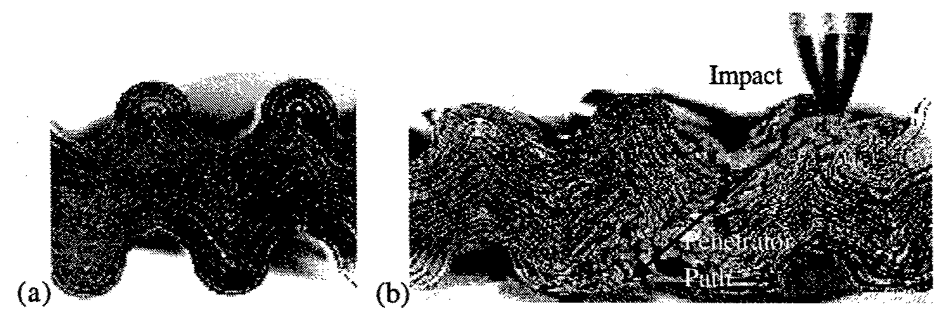


Fig. 5. (a) Corrugated MIL Composites (b) Ballistic Impact of Corrugated MIL composite.

An appropriately sized wire of Ti, for example, can then be stitched through the array of holes. Once reacted, the Ti wire will partially react with the foils, bonding the wire between the layers; however, since a central portion of the Ti wire will remain unreacted, the wire will provide three-dimensional strengthening. Figure 5 shows a cross-section through a MIL composite that was successfully wire stitched in the through-

Thickness direction

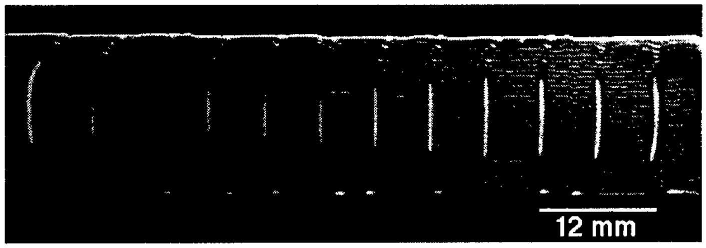


Fig. 6. Cross-section of a wire-stitched, through-thickness strengthened MIL composite

5.0 MIL Composites Incorporating Ceramics for Enhanced Ballistic Performance

Since the MIL processing is carried out at very low pressures, it is relatively easy to incorporate monolithic or composite ceramic materials directly in the layering to form metallic-intermetallic-ceramic composites. As such, production of tiled, brick and mortar, and inclined layered structures can be fabricated. By drilling holes and creating cavities within the Al foil layers and embedding ceramic tiles or ceramic particles, it is possible to create confined ceramic regions with the hardened intermetallic layers that form during reactive sintering of the MIL composites. Figure 7 shows an example of boron-carbide particulate reinforced intermetallic layer in a Ti-Al MIL composite. Embedding ceramic tiles within the intermetallic layer allows the design of significantly increased hardness of the overall composite. Figure 8a shows an initial Al foil containing an array of ceramic tiles. Using a series of these layers, stacked in an FCC-type ABC-stacking sequence, it is possible to create a structure with no path through the thickness that does not involve interaction with at least one ceramic tile (Figure 8b). Figure 8c shows a cross-section through the sample of Figure 8b having been impacted by a WHA penetrator. This method of incorporating ceramics within the MIL composites may offer tremendous potential for future developments of significantly improved ballistic materials.

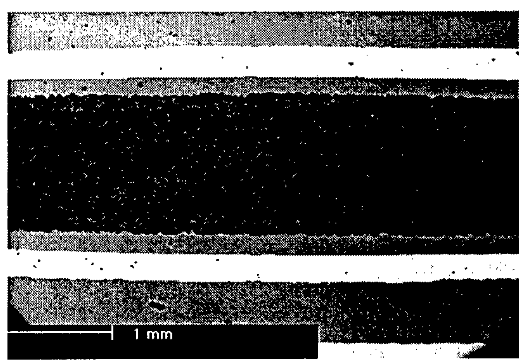


Fig. 7. MIL Composite containing a cavity filled with boron-carbide particulate creating a cermet-type region within the intermetallic layer.

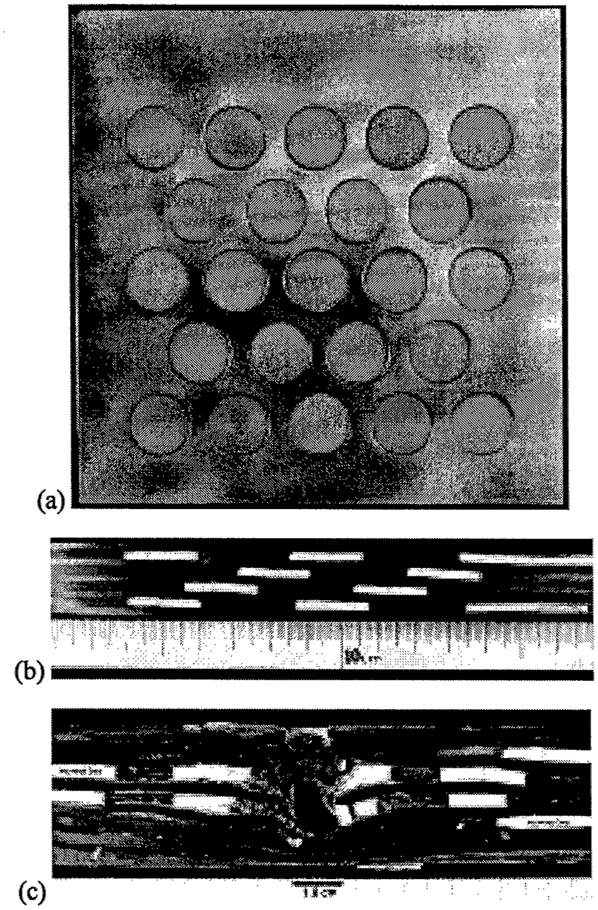


Fig. 8. (a) Al foil layer containing a hexagonal array of alumina ceramic disks, (b) Cross-section through reacted sample containing the alumina disks, and (c) Cross-section through alumina disk reinforced sample impacted by a WHA penetrator at 900 m/s.

CONCLUSIONS

Although we feel that we have made tremendous progress in developing a new class of armor materials with great potential for lightweight structural armors, we also strongly feel there is good reason to continue funding more ballistic development work on these materials. Clearly, these materials would benefit from a detailed computational modeling effort to optimize the microstructure and meso-structures of these materials for ballistic protection. For these modeling efforts to be successful, they must be verified and guided by further ballistic testing.

SCIENTIFIC ACCOMPLISHMENTS UNDER DIRECTION OF PROFESSOR MARC MEYERS

Dynamic Modeling and Processing of Materials for Dynamic Performance

Research directed by Prof. Marc Meyers
Supporting graduate students James Shih Elizabeth Strutt and Q Xue, and Q. Liu (Postdoctoral Researcher)

1.0 Biomimetic Materials (Marc Meyers, R. Menig - graduate student - U. of Karlsruhe, M. H. Meyers - UCSD-Biology Dept.)

This exploratory work was completed and two papers are being published. This work is inspiring processing efforts directed by Ken Vecchio on laminate structures and by this investigator on metal-ceramic

laminates (see item 4 below). The paper on abalone is already in print in *Acta Materialia.* The paper on conch was conditionally accepted by *Materials Science and Engineering* and should appear in late 2000. Discussions are currently under way to explore other biological systems for possible application in military structures.

2.0 Resilient Materials (Marc Meyers and Elizabeth Strutt, Collaborators: Sia Nemat-Nasser and Jon Isaacs)

In this research, TiC-NiTi composites have been produced by self-propagating high temperature synthesis (SHS) combined with quasi-isostatic pressing (QIP) in a granular pressure transmitting medium. Compositions with 20, 30, 40, 60 and 80 volume percent NiTi have been prepared. The chemistry has been optimized to prevent formation of Ni3Ti. Differential Scanning Calorimetry (DSC) has been performed on the various cermets and has confirmed that the martensitic transformation can be induced by changes in temperature, even in those composites that have a rigid, interconnected ceramic skeleton. Quasi-static compression tests have been performed to study the room temperature response of TiC0.7-30NiTi. Preparations are being made to test the TiC0.7-30NiTi composites slightly below Ms to determine if stress induced martensite forms in composites with high ceramic content. Ballistic testing of the TiC0.7-30NiTi composite with a 1090 steel projectile fired at 500 m/s resulted in defeat of the projectile with no visible penetration of the composite. Targets are being machined for more systematic ballistic tests. The following papers were submitted for publication: "Self-Propagating High-Temperature Synthesis and Densification of Powder Cermets," Strutt, Olevsky, & Meyers, *Materials Science and Engineering* –submitted; and "Characterization by Indentation of Combustion Synthesized Cermets," Olevsky, Strutt, & Meyers, *Scripta Materialia* – submitted.

3.0 Damage in Silicon Carbide (Collaborators: Vitali Nesterenko, L. W. Meyer-U. of Chemnitz, Germany, David Benson)

A combined experimental-computational program is in progress to establish the constitutive response of damaged SiC. This behavior is very important because the ceramic is comminuted upon impact. Dr. James Shih has made significant progress in the past. It is expected that the program currently under way will lead to quantitative assessments of the mechanical response of SiC as a function of confining pressure. This will be coupled with physical modeling of the phenomena and implementation into computational codes. A paper dealing with damage in SiC is in press in *Acta Materialia.*

4.0 Ceramic-Metal Laminates

(Collaborators: Ken Vecchio, H. C. Bryan Chen – Cercom, Q. Liu Post-Doctoral Researcher, Q. Xue, Ph.D. candidate)

This area of research is being initiated and could lead to novel structures well suited for armor applications. Cercom has the capability and know-how for the fabrication of SiC layers by tape casting. Preliminary experiments are being conducted to establish whether the system investigated (SiC-Ti) present's favorable reactions. Past work on B4C-Al yielded reaction products that were very deleterious to the integrity of the structures.

CONCLUSIONS

This MURI was instrumental in four important developments.

The work carried out by Dr. Shih (currently Manager for New Materials, CERDYNE) is being recognized as seminal in the area of dynamic behavior of ceramics. He experimentally demonstrated that comminuted SiC undergoes shear localization and developed an analytical model that addresses the physical phenomena involved. The microstructural evolution in the dynamic deformation of SiC was investigated in the same study and the effect of dislocations and politypes was demonstrated. The role of microplasticity in failure initiation was demonstrated. This work was recognized in Europe, and Dr. Shih received the best thesis award from the EURDYMAT Association , in Krakow (2000). He gave an invited lecture at that meeting.

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The work of Dr. Xue (currently Post Doctoral Fellow at LANL, working in Dr. Gray's group) dealt with the collective behavior and microstructural evolution in shear localization. Dr. Xue demonstrated that shear bands self-organize with an evolving spacing, that is size dependent. He developed an analytical model that includes the two-dimensional effects and is based on stress shielding. The microstructure within the shear bands revealed the microcrystalline structure observed earlier for other metals. A quantitative model was developed based on grain-boundary diffusion and compatible with rotational dynamic recrystallization. A novel microstructure was revealed (quite serendipitously) and confirmed for a second alloy: amorphous regions within the shear bands, due top the extreme rates of heating and cooling. This is the first report of amorphization induced by shear localization.

Additional successful activities included the demonstration that Ti ands SiC can be bonded by reaction. This could yield a laminate composite with superior armor performance. This exploratory research should be continued. The synthesis and processing of resilient TiC-NiTi cermets has been carried out successfully and ballistic tests showed excellent performance.

A fourth component of the program has been interrupted. Joint experiments planned with Prof. L. W. Meyer could not be carried out, but it is hoped that modest funding will be made available by ARO to complete this program.

SCIENTIFIC ACCOMPLISHMENTS UNDER DIRECTION OF PROFESSOR VITALI NESTERENKO

Part I: Behavior of Solid and High Gradient Targets from HIPed Ti-6Al-4V at the Different Conditions of High Velocity Impact (plugging and penetration modes)

Part II: Controlled Magnetically Driven High Strain Rate 2-D test of Ti and Stainless Steel

Research directed by Prof. Vitali Nesterenko

Supporting Gu YaBei, Graduate Student Researcher and Sastry S. Indrakanti Postdoctoral Researcher.
Dayton Research Institute).

Collaboration: Part I: Werner Goldsmith (UCB), N.S. Brar (University of Dayton Research Institute); Part II: John L. Stokes, Jack S. Shlachter, Robert D. Fulton, (Los Alamos National laboratory, Los Alamos).

1.0 Synthesis and Processing of Armor Materials and Composites (V. Nesterenko and W. Goldsmith)

Hot isostatic pressing was used to manufacture a variety of porous composite samples where powder (B_4C) filed tubes of Al_2O_3 were placed in the matrix of Ti-6Al-4V in combination with rods and plates under different angles to the impact direction. Modeling of residual compressive stresses in ceramics inserted by HIPing into matrix of Ti-6Al-4V was performed.

2.0 Experimental characterization (V. Nesterenko, N. S. Bar)

The samples from previous ballistic penetration test (in collaboration with N. S. Brar, University of Dayton Research Institute) with tungsten (93 %) heavy alloy penetrators (velocity 886-960 m/s, mass 16.8 gram, diameter D=4.93 mm, L/D=10) with solid and porous composite samples of Ti-6Al-4V alloy with different microstructures (Widmanstatten pattern and equiaxed) were investigated. Penetration depth for HIPed materials are smaller than in baseline samples of Ti-6Al-4V alloy (forged rod MIL-T-9047G). Composite materials with alumina rods and tubes filled with B_4C powders demonstrated new features of penetration: projectile deflection with self sealing of hole and forced shear localization caused by tube fracture.

Hopkinson bar testing of solid HIPed samples was performed in collaboration with S. Nemat-Nasser.
New ballistic tests are scheduled in newly processed samples at University of Dayton Research Institute and in UC Berkeley.

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3.0 Development of New Experimental Techniques (Vitali Nesterenko, John L. Stokes, Jack S. Shlachter, Robert D. Fulton, (Los Alamos National Laboratory)

The first controlled two-dimensional high-strain-rate experiments were performed in the geometry similar to the thick walled cylinder, but using magnetically driven implosion at the Pegasus-II facility in collaboration with LANL (J.L. Stokes, J.S. Shlachter, R. D. Fulton). Comparative behavior of Ti and 304 stainless steel was investigated. A pulsed power capacitor bank capable of delivering several megamperes of current to a cylindrical conducting liner, was used for the magnetic implosion of a thick walled cylinder to study two-dimensional high-strain-rate flow in different materials. Boundary conditions of loading (dynamic pressure) were monitored by the measurement of magnetic field outside of the composite cylinder. The kinematics of flow was measured using three radial X-ray radiographs at different azimuthal angles and different times after the start of current through the cylinder. The relative azimuthal angles were 0; 120, 240 degrees and radiographs were obtained at 13, 18 and 30 microseconds following current start. Peak current from the capacitor bank occurred at 8 microseconds. It was demonstrated that a magnetically driven composite thick walled cylinder is able to preserve cylindrical symmetry at the level of large strain enough to initiate material instability and at the same time avoid geometric instability typical for thin walled cylinders. The composite liner consisted of separate stacked cylinders of stainless 304 and Ti. The results are contrary to the expected behavior based on uniform plastic flow of these materials. This is explained based on the plastic flow instability and formation of multiple shear bands. The technique may be used for testing of 2-D and 3-D numerical models under controlled boundary conditions and detail kinematics of plastic flow.

CONCLUSIONS

Powder-based, texture-free homogeneous and high gradient samples with embedded ceramic roads and powder filled ceramic tubes of armor were processed from Ti-6Al-4V powder using optimized hot isostatic pressing. Ballistic testing of processed target against impact by conical, blunt and long rod projectiles demonstrated better performance in comparison with commercially available Ti-6Al-4V alloy MIL-T-9047G with best combination of strength and ductility. Elastic and dynamic properties of powder based material were fully characterized. Qualitatively new complex pattern of shear bands was found in powder-based material under high strain, high strain rate deformation which is probably responsible for imporved ballistic performance. New mechanism of long rod deflection based on forced shear instability due to collapse of powder filled voids was demonstrated in high-gradient materials.

Self organization of shear bands was investigated in different materials and first experimental results were obtained for verification with proposed theories of Grady-Kipp, Wright-Ockendon, and Molinari. The lack of self organization stage was established for Ti-6Al-4V in striking contrast with Ti and stainless steel at the same conditions of testing.

Shear instabilty in damaged SiC was established as a major mechanism of high strain, high strain rate flow. New phenomena of SiC resintering inside shear band and its dependence on particle size was discovered. Influence of grain size and porosity on shear band pattern was demonstrated revealing the stabilization of high strain flow by low level of initial porosity.

Mechanism of anomalous shock attenuation was established in laminar materials like Ti-Al composite.

V. INTERACTION WITH DOD, DOE LABORATORIES, INDUSTRY, AND UNIVERSITIES AND TECHNOLOGY TRANSFER

- Sia Nemat-Nasser: Dr. T. Wright (ARL), visited CEAM March 1998.
- Sia Nemat-Nasser: collaboration with Professor John Willis (Cambridge, UK) on micromechanical modeling of dynamic deformation and failure modes of heterogeneous structures, involving several length scales.
- David Benson; Interaction with Professor Wing Kam Liu (Northwestern University), whose graduate student developed a research code for Benson's new method for calculating the time step size.

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- Sia Nemat-Nasser: Presented a well attended informal seminar at ARL, on June 7, 1999, on mechanics of ceramic penetration process, to Dr. William J. Gillich and his group. Extensive discussion followed the seminar.

- Vitali Nesterenko:: Discussions with Drs. William A. Gooch, Hubert W. Meyer during Conference on Shock Compression of Condensed Matter, American Physical Society meeting, Snowbird, Utah, 27th June 3 July; discussion with Dr. Thomas W. Wright on magnetic implosion test for comparison of self organization of shear bands in Ti and stainless steel.

- Ken Vecchio: collaboration with Rusty T. Gray, III, Los Alamos National Laboratory, collaborating on Dynamic Testing of the MIL composites, in particular the Taylor Testing as a function of orientation.

- Ken Vecchio: collaboration with Ernie Chen, Army Research Laboratory, collaborating on the synthesis of novel MIL composites for signature control using trilayer MIL composites of metal-intermetallic -ceramic combinations.

- Dave Benson: Organized ASME IMECE 2000 Symposium on Computational Micromechanics with the collaboration of Scott Schoenfeld.

- Sia Nemat-Nasser: Extensive interaction with Aerojet/Gencorp (Mike Stawovyy, Henri Kim, and B.C. Chouck), on high deformation experimentally-based modeling of high strain rate response of tantalum.

- Sia Nemat-Nasser: Collaboration with Dr. Tim Wright, (U.S. Army Research Laboratory, Terminal Effects Division) visited CEAM February 6-26, 2000.

- Sia Nemat-Nasser: Continued interaction with Aerojet (Mike Stawovyy, Henri Kim, and B.C. Chouck), on high deformation experimentally-based modeling of high strain rate response of tantalum.

- Vitali Nesterenko: Continued collaboration with Dr. Werner Goldsmith, UC Berkeley, on the synthesis and processing, new characterization and ballistic evaluation of solid and graded armor materials. Professor Goldsmith visited UCSD in October 1999 and February 2000.

- Vitali Nesterenko: Collaboration with Dr's. J. Shiachter, J. Stokes & R. Fulton from Los Alamos National Laboratory on research pertaining to magnetically driven thick walled cylinder testing.

- Marc A. Meyers: Continued collaboration with R. Menig (Graduate Student from U. of Karlsruhe) on the research pertaining to biomimetic materials in relation to modeling and processing of materials for dynamic performance.

- Marc A. Meyers: Continued collaboration with Lother W. Meyer (University of Chemnitz, Germany) on damage of silicon carbide in relation to modeling and processing of materials for dynamic performance.

- Marc A. Meyers: Continued collaboration with Dr. H.C. Bryan Chen from CERCOM Inc, on ceramic-metal laminates in relation to modeling and processing of materials for dynamic performance

- Ken Vecchio: Continued collaboration with Rusty T. Gray, III, Los Alamos National Laboratory, collaborating on Dynamic Testing of the MIL composites, in particular the Taylor Testing as a function of orientation.

- Ken Vecchio: Ernie Chen, Army Research Laboratory, collaborating on the synthesis of novel MIL composites for signature control using trilayer MIL composites of metal-intermetallic -ceramic combinations.

- Dave Benson: Organized ASME IMECE 2000 Symposium on Computational Micromechanics with the collaboration of Scott Schoenfeld.

- Sia Nemat-Nasser attended PacRim IV, Maui, HI, November 4-8, 2001 and made a Keynote Presentation in the session organized by Dr. David Stepp on Damage Evolution and Micromechanics. Title of presentation: "Micromechanisms of Compression Failure"

- Sia Nemat-Nasser attended PacRim IV, Maui, HI, November 4-8, 2001 and made an Invited Presentation in the session organized by Steve Wax on Ultra-Lightweight Transparent and Novel Concepts. Title of presentation: "Novel Ideas in Multi-Functional Ceramic Armor Design"